"SPACE REQUIREMENTS FOR THE COMBUSTION OF DISTILLATE FUEL"

by
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May 20, 1949

SPACE REQUIREMENTS
FOR THE COMBUSTION OF DISTILLATE FUEL

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Professor J.S. Newell
Secretary of the Faculty
Massachusetts Institute of Technology
Cambridge, Massachusetts

Dear Sir:

In accordance with the requirements for the Degree of Naval Engineer, I submit herewith a thesis entitled "Space Requirements for the Combustion of Distillate Fuel."

Respectfully,

ACKNOWLEDGMENT

The author wishes to express his appreciation to Professor H.C. Hottel for his assistance and advice, in addition to the original suggestion which prompted this investigation.

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TABLES AND FIGURES

I. SUMMARY

The problem of space requirements for the combustion of industrial fuels in furnaces has not often been approached with methods other than the application of previous experience. An outstanding example of a theoretical analysis of space requirements, which was successfully applied to operating data, is the paper by Hottel and Stewart (6) on pulverized coal. They combined a knowledge of the combustion process for a single coal particle with a size distribution law for pulverized coal and suitable assumptions concerning the combustion of a cloud of particles. The data used were obtained from a furnace of industrial size.

This problem of space requirements resolves into the determination of the completeness of combustion within a given time. For fuel oils, the factors affecting the completeness of combustion in a furnace are: (1) nature of the oil, (2) air-fuel ratio, (3) particle size, (4) temperature of the furnace, (5) furnace atmosphere, (6) relative velocity between particles and surrounding gases, and (7) the time spent in the furnace.

The object of this study was to test the possibility of obtaining reliable operating data from an experimental furnace. It was hoped that such data could be analyzed to form a correlation of the factors affecting completeness of

combustion of one fuel oil. Thus, the reverse of the method used by Hottel and Stewart for pulverized coal was to be applied to a fuel oil.

The experimental furnace was designed and built by Newton, Simpson and Vincent (8). Fortunately, the furnace was designed to use air atomization of the fuel, which permitted the use of the equation of Nukiyama and Tanisawa (9) for predicting the mean drop diameter of the fuel spray.

By applying this equation and using only one fuel oil, the remaining factors affecting completeness of combustion are either controllable and measurable or estimable.

A few alterations were required to adapt the existing equipment to the present purpose. The experimental procedure consisted of conducting runs at constant fuel rate and varying the air-fuel ratio from run to run. The air rate, fuel rate, furnace temperatures, exhaust gas temperature, fuel temperature, and combustion air temperature were all measured. A gas analysis of the exhaust gases was made from an average sample for each run.

Difficulties experienced with the fuel supply system and the gas analysis unit thwarted the attempt to obtain data of sufficient accuracy to permit a correlation. The arrangement of the fuel-atomizing assembly permits an unnecessary cooling of the fuel spray at high air-fuel ratios.

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arrangement of the fuel-air mixing assembly, as well as the

necessary cooling of the fuel spray at high air-fuel ratios.

The equipment, as tested, is neither adequate nor satisfactory for the present study. By incorporating the changes found necessary as a result of the present investigation, the equipment could be used for a profitable study of the factors affecting completeness of combustion of fuel oils. The effects of air-fuel ratio, drop size and residence time could be studied independently.

II. INTRODUCTION

One possible approach to the problem of determining the space requirements for the combustion of a fuel is to gather reliable operating data on a typical combustion chamber, then, by judicious selection of parameters, correlate these data into usable form. Another possibility is to apply the theories of combustion, kinetics of gases, and heat transfer to an idealized combustion chamber, with appropriate simplifying assumptions, and evolve an equation in which the space requirement is given as a function of the many variables involved. Such an equation would then have to be modified to fit practical combustion chambers by the application of constants obtained from actual test data. When the fuel in question is of complex composition and is of such physical form that particle-size distribution is an important factor, the latter procedure becomes exceedingly complex. The combustion of distillate fuel is of this nature; therefore the first approach was attempted in this investigation.

Although the first approach is applied to the problem, the number of variables involved remains large. The first step in the solution is to eliminate as many of the variables as possible by the proper choice of equipment and procedure; then maintain control of as many more of the variables as possible. This was the general plan in this

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investigation. The ultimate end was to be a curve of the fraction of the fuel left unburned at any time versus a time factor. Such a curve, or family of curves, could then be used to predict the required size of other combustion chambers of similar construction, using the same fuel. If this investigation were carried further to include other types of combustion chambers, a series of curves could then be produced for use in the design of any combustion chamber in which the same fuel is to be used.

An excellent example of the second method of approach, mentioned above, is the work of Hottel and Stewart (6), which provided the inspiration for the present work. It is firmly believed that the space requirements for the combustion of fuel oils can be obtained by the same general method as used by Hottel and Stewart to obtain the space requirements for the combustion of pulverized coal. Their method consists of a correlation of a size distribution law for pulverized coal particles with the laws of burning individual particles and suitable assumptions applicable to the combustion of a cloud of particles. A more complete account of the methods applied to the problem of space requirements for combustion is given in the Appendix.

The work of Nukiyama and Tanisawa (9) provided the size distribution law for fuel oil using air atomization, which is applied in this investigation. There is not,

however, any law for the combustion of individual particles of distillate fuel available in the literature. Chang (2) studied the combustion of individual drops of heavy fuel oil; however his findings are not applicable to distillate fuel because of the differences in composition. The lack of knowledge of the combustion characteristics of individual distillate oil particles imposed a serious handicap on the present investigation. It was felt, however, that with the results of Hottel and Stewart as a guide, this handicap could be overcome.

The real cause of interest in the space requirement for the combustion of distillate fuel is the promise which gas turbines hold for power plants, both mobile and stationary. At present, the fuel which seems quite likely to be used in the combustion chamber of the gas turbine power plant is distillate fuel. Thus, one object of this study was to provide data and information useful in the design of gas turbine combustion chambers. Such combustion chambers are necessarily of very high capacity and contain little or no heat transfer surfaces. It was, therefore, desirable to use such a combustion chamber for this study. Newton, Simpson and Vincent (8) designed and built a combustion chamber of this type, incorporating air atomization, for their study of the formation of stack solids from the combustion of heavy fuel oil. Their combustion chamber was

designed to have the capacity of a naval, express-type, boiler furnace; and, although the desired capacity is almost double that, it was decided to use this combustion chamber to test its suitability for the present type of investigation.

As shown from previous work (2), (6), (7) and (8) the factors affecting the completeness of combustion of a fuel oil in a furnace are: (1) the nature of the oil, (2) the air-fuel ratio, (3) particle size, (4) temperature, (5) furnace atmosphere, (6) relative velocity between the particle and surrounding gases, and (7) the time in the furnace. For the present investigation it was assumed that all these factors would be known, calculable or measurable to a sufficiently accurate degree for each test to permit their correlation.

The Equipment

The arrangement of the equipment is shown in Figures I, II and III. This arrangement is the same as was used by Newton, Simpson and Vincent (8) with the following exceptions:

(1) the gas-sampling fitting was moved from its location after the cyclone separator to a position just before the cyclone separator;

(2) The gas-sampling fitting was equipped with a water-cooled coil;

(3) the gas sample was drawn into a large glass container over a 20% NaCl and 5% H_2SO_4 solution by syphon action;

(4) the fuel line from the fuel reservoir was fitted with a coupling to permit easier handling; and,

(5) in the later stage of the present study, the fuel reservoir was moved vertically upward ten feet and five inches.

The equipment consists of the following components:

Furnace - The furnace is a long chamber of small square cross-section fired down-draft. The small cross-section minimizes variation of the path length of the particles of fuel. There is no provision for temperature control of the furnace, except during the warm-up period, the temperature being dependent upon the firing rate and excess air. The furnace casing is fitted with small openings to permit visual observation, temperature measurement and pressure measurement. The top section is fitted with connections to permit the use of city gas in warming up the furnace prior to a test run. The lowest section of the furnace may be removed to change the furnace volume; however this feature was not utilized. The furnace lining is a dual-purpose refractory and insulating brick. The details of the furnace are shown in Figures IV and V.

Quenching Unit - The purpose of this unit is to stop

combustion by cooling the gases as they reach the end of the furnace; thus the volume available for combustion is a known quantity, provided that the flame remains at a fixed position. The unit consists of a single row of thin-walled, 2" diameter, copper tubes flattened and placed with their long dimension in the direction of the gas flow. The side walls of the unit are water-cooled. It is possible to vary the water flow rate through the unit over a considerable range, the upper limit being fixed by the allowable pressure within the tubes. Too high a pressure causes leaks; but, with careful handling, the unit performs quite satisfactorily. It is possible to cool the gases from temperatures in the vicinity of 2100°F. to 1100°F. in their short travel through the unit.

<u>Fuel Supply</u> - The fuel supply consists of a gravity-feed reservoir of one-gallon capacity with a supply line, valve-controlled, ending in a fuel orifice. The cover of the reservoir is fitted with a thermometer well for use in measuring the fuel temperature. Originally, and during the major portion of the present study, the reservoir was suspended just above the furnace. After half the test runs had been conducted it was decided that the changing level of the fuel had too large an effect on the fuel rate. The reservoir was then relocated in a position 10'-5" above its original position so that the total head was 13'-9". This

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was done on the basis that a change of head of the fuel oil of ten or twelve inches during a test run would not affect the fuel rate appreciably; the fuel rate would, therefore, be constant. This change introduced a new problem, however, because with such a large total head the fuel rates were excessively high, even with a very small fuel orifice. Throttling the fuel flow with the throttle valve was not successful because the throttle valve became clogged, although the fuel was strained through 100-mesh wire screen before being placed into the reservoir. Finally, this difficulty was overcome by installing a fuel strainer consisting of two 200-mesh screens in series in the fuel line just above the throttle valve.

Fuel Atomizer - Air atomization was used primarily because the method of Nukiyama and Tanisawa (9) could be used to evaluate the mean drop size. Further discussion of this method, and details of the theory, are given in the Appendix. Another advantage of this method of atomization is that wall-impingement of the fuel particles is minimized. For this particular arrangement there is the disadvantage that all the combustion air is introduced into the furnace with the fuel, which causes undue cooling of the stream at high air-fuel ratios. This aspect will be discussed further in the Results, Conclusions, and Recommendations. The fuel atomizer assembly is shown in Figure VI.

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Separating Unit - The cyclone separator is an integral part of the exhaust, and was left intact. Its function was not necessary in the present study; however, its presence in the system was not objectionable. The function of the separator is to collect stack solids from the combustion of heavy fuel oils.

Control and Measuring Instruments -

1. Air - An ASME sharp-edged orifice with vena-contracta pressure taps was used to meter the air. The air was supplied by a motor-driven blower with a constant-pressure characteristic. Considerable difficulty and delay were experienced with this blower at the beginning of the experimental work because of faulty bearings and poor alignment. A by-pass valve is installed for the purpose of controlling the quantity of air delivered. This valve was left wide open, because more reliable control was provided by the air atomizing-orifice in use. The blower has a capacity of 126 cu.ft./min. when discharging to the atmosphere; but when connected to the furnace through the atomizing assembly the capacity was reduced to a maximum of 76 cu.ft./min. at 9.2" of water.

2. Temperatures - Fuel and air temperatures were measured by thermometers. The temperature of the combustion air was measured by a thermometer placed in a perforated well in the air duct about 2-1/2 feet from the atomizing

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well in the air duct about 2-1/2 feet from the atomizing

assembly. Chromel-alumel thermocouples were used to measure the furnace and exhaust gas temperatures. The furnace thermocouples are installed in alundum protection tubes as shown in Figure V. The exhaust gas thermocouple is fitted with a single cylindrical shield. An ice bath was used for the cold junction of the thermocouples. The readings were made with a Leeds and Northrup double-scale potentiometer. The location of the thermocouples is shown in Figures I and II.

3. Gas Sampling Equipment - Rather than taking one or more small samples of exhaust gas during a test run, which would apply to more or less instantaneous conditions of combustion, a large-volume sample was collected during the major portion of each run. The gas-sampling fitting consists of a perforated copper tube extending across the exhaust duct on the centerline. The exterior portion of the copper tube is water-cooled by a coil wrapped around the tube. The gas sample is drawn into a large glass bottle by the syphon action of a saturated salt solution flowing from the sample bottle. A small sample was later withdrawn from the large sample bottle for analysis. The arrangement of this equipment is shown in Figure I.

4. Gas Analysis Equipment - A Fisher, unitized, precision gas analysis unit was used. The unit was equipped with burettes for the absorption of CO_2, O_2 and CO and a

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5. Pressures - Water manometers were used to measure the pressures in the air duct and the furnace. Atmospheric pressure was measured by means of a standard, mercury barometer.

6. Humidity - A sling psychrometer was used to measure the humidity in the room.

FIGURE I

ARRANGEMENT OF EQUIPMENT

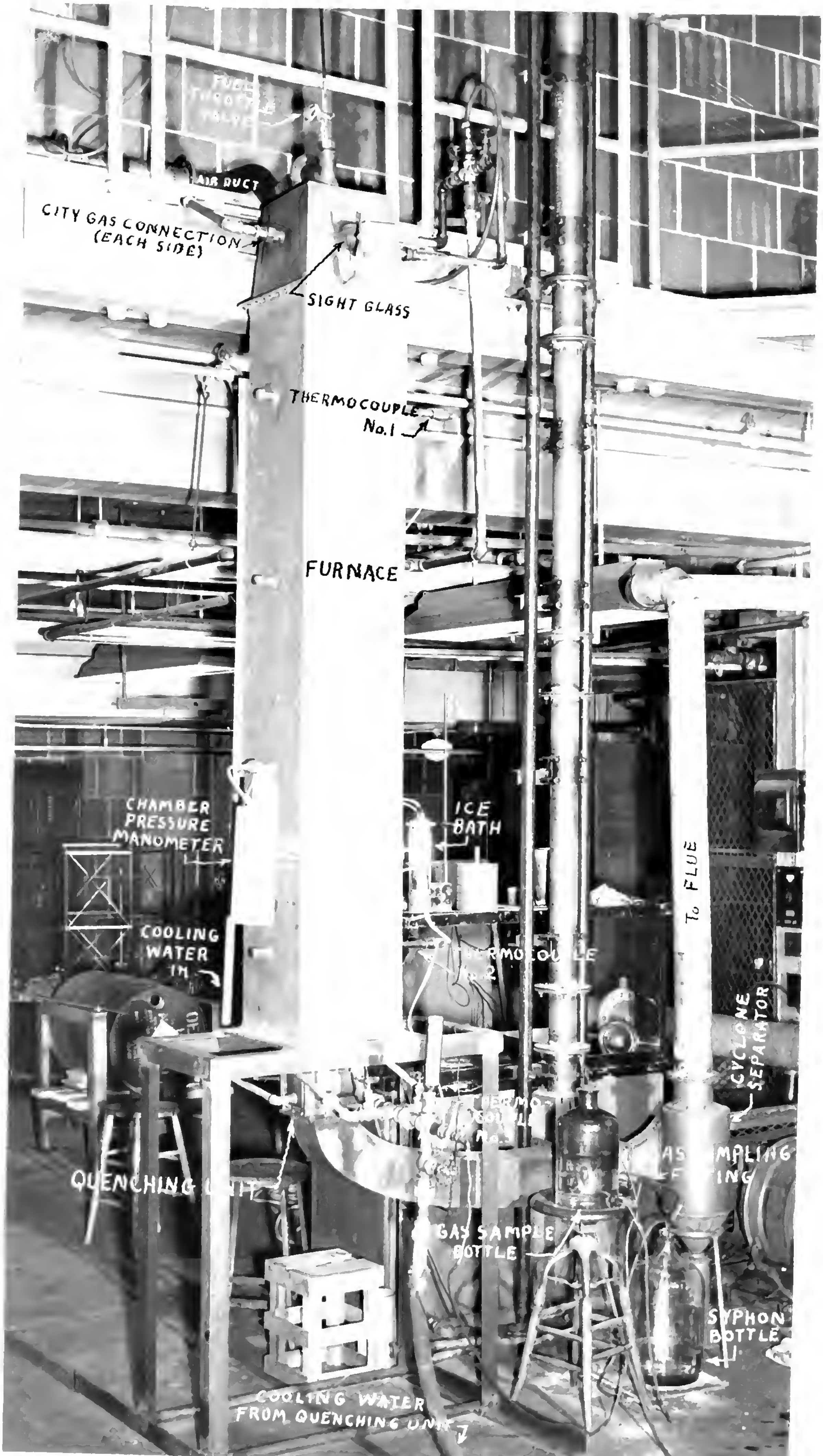


FIGURE II

ARRANGEMENT OF EQUIPMENT

FIGURE III

ARRANGEMENT OF EQUIPMENT

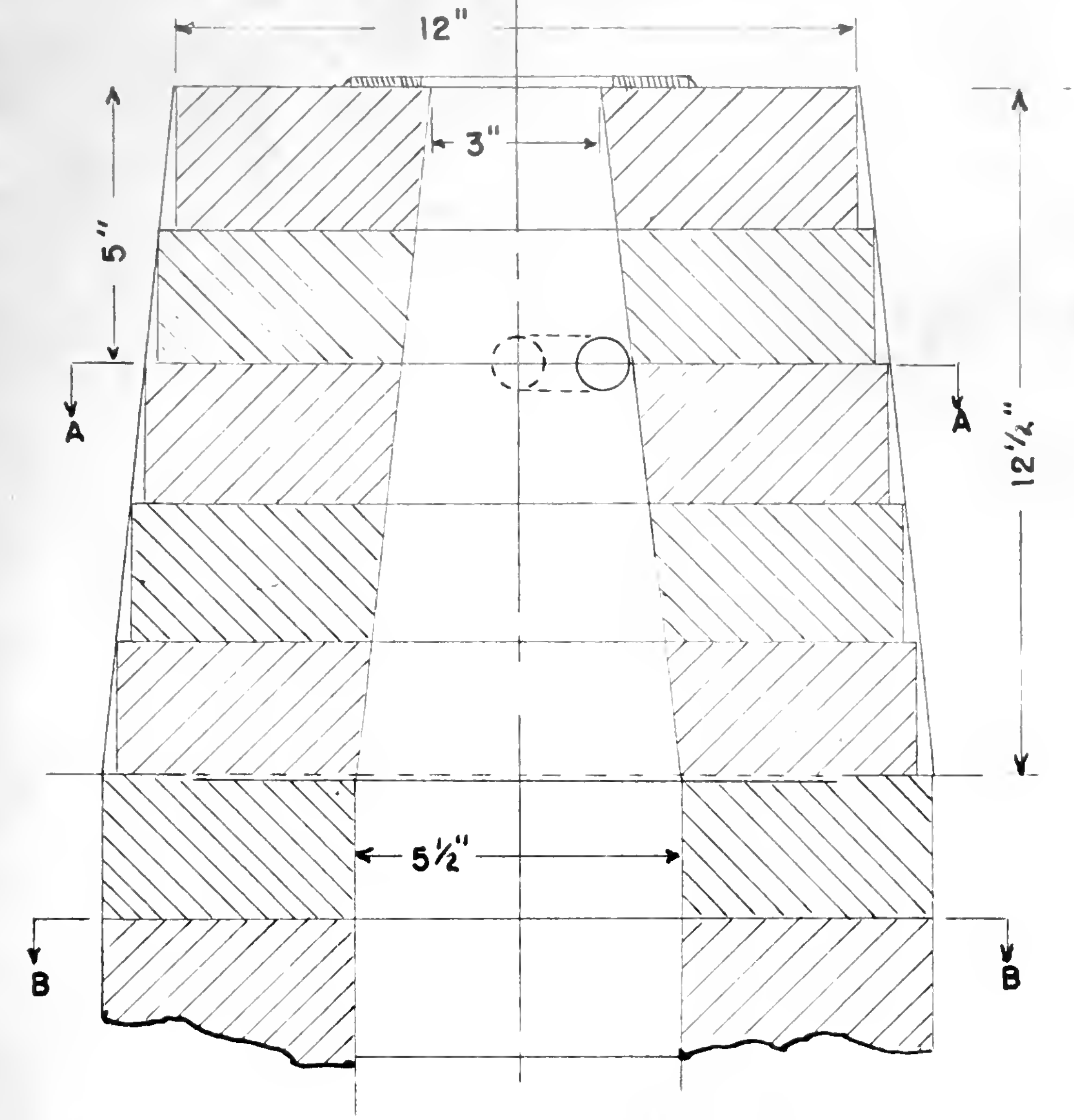
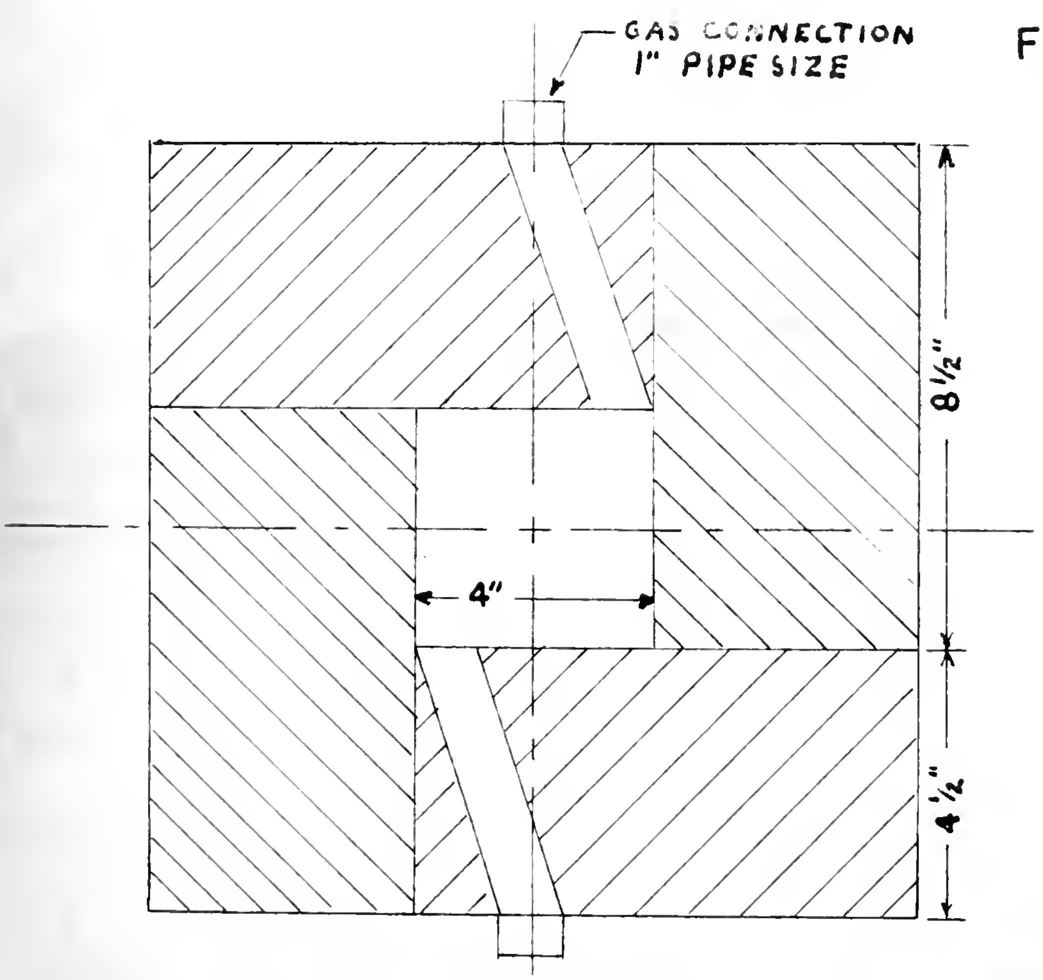


FIGURE IV

FURNACE CROSS - SECTIONS

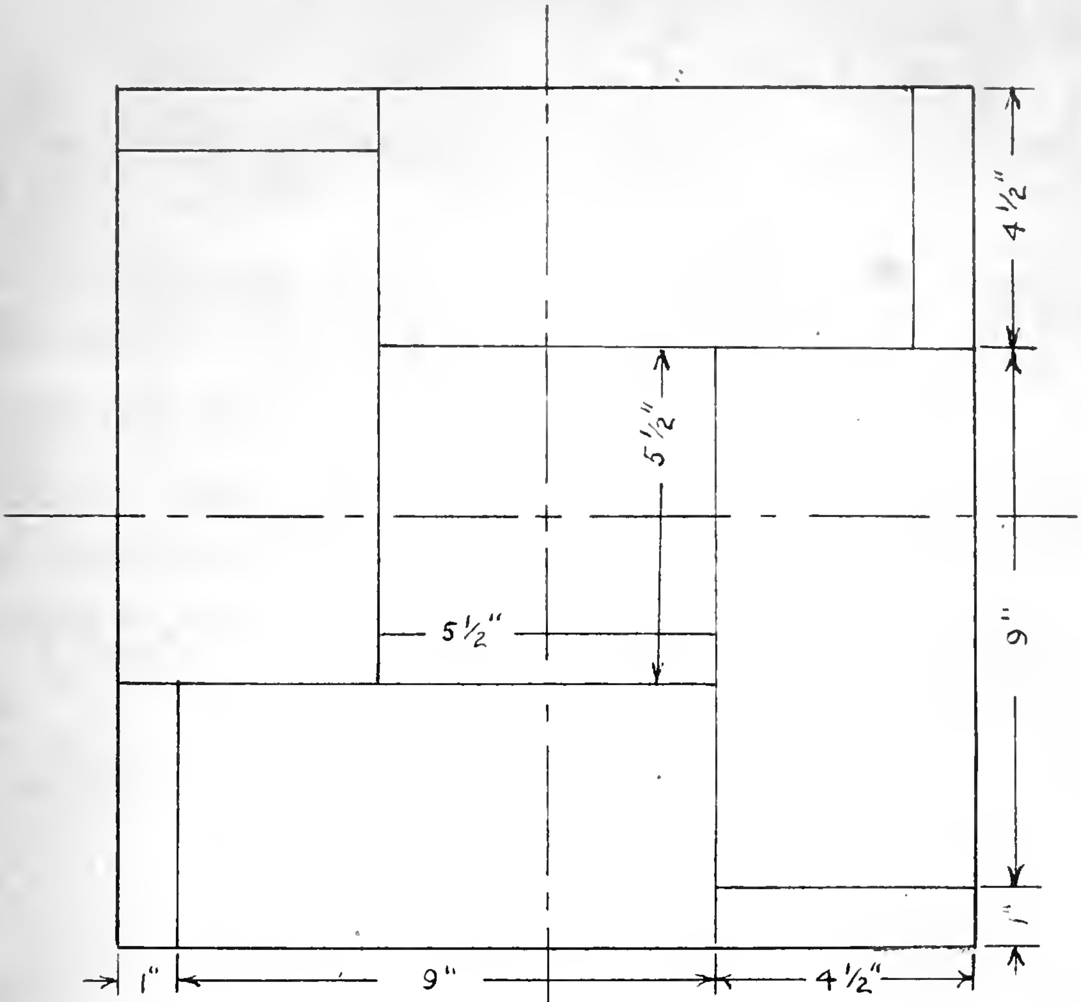


SECTION A-A

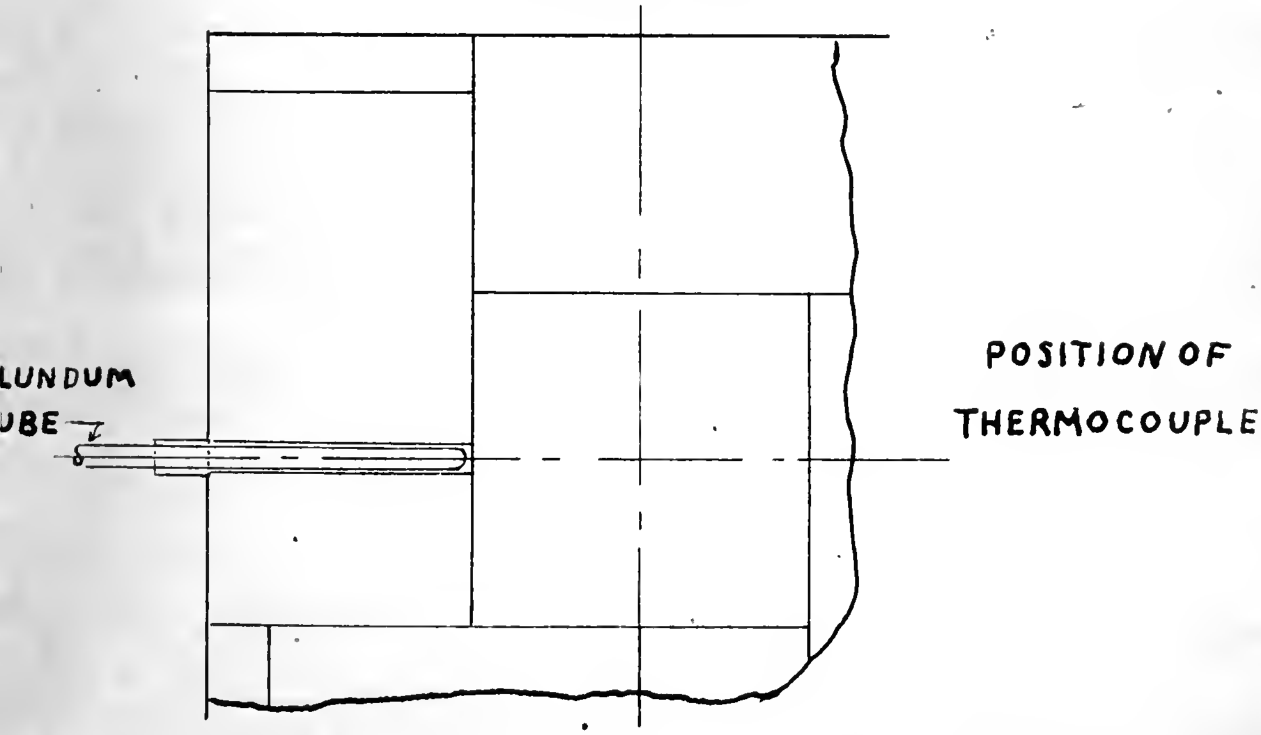
REPRODUCED FROM REFERENCE (8)

FIGURE V

FURNACE CROSS-SECTIONS



SECTION B-B



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III. PROCEDURE

The procedure was divided into three distinct steps as follows: (1) preliminary work concerned with the assembly and alteration of the equipment and trial runs, (2) the data-taking runs and gas analyses, and (3) the calculation and analysis of the results.

1. Preliminary Work - The first problem was a consideration of how the existing equipment could be adapted for use and the changes required in order to effect the adaptation. Only minor changes were considered necessary and these have been previously noted. Parts of the equipment had been disassembled; these were inspected, then reassembled, and the alterations were performed. The fuel orifice was tested and reduced in size so that a flow rate of 0.2 lb./min. was obtained. A preliminary trial run was started, using city gas; but had to be stopped because of the very poor condition of the blower-motor bearings. Upon reinstallation of the blower-motor, after the bearings had been repaired, a full trial run was made to test the proposed procedure in the conduct of the runs. The procedure was found to be satisfactory; but the blower-motor bearings failed because of improper repair. Another blower was obtained, an adaptor and foundation were constructed and the blower tested in the equipment. This new blower was unsatisfactory because it quickly overheated. Meanwhile,

the bearings of the first blower had been properly repaired and aligned; the first blower and motor were then reinstalled. Two more trial runs were made in order to gain familiarity with the equipment, make minor changes in the procedure and to standardize the method of making the readings.

2. Data-taking Runs - The general plan for making the runs was to start with a small-sized fuel orifice to obtain a low fuel rate. For each run a different air atomizing-orifice plate was used, thus obtaining a different air rate to give a different air-fuel ratio for each run. Orifice plates with diameters 1.00", 1.10", 1.20", 1.30" and 1.40" were used. The air rates were varied in this manner from 37.5 cu.ft./min. to 76 cu.ft./min. After a series of runs was completed using all the orifice plates, the size of the fuel orifice was increased to give a higher fuel rate and the series of runs was repeated.

The procedure for an individual run was as follows:

(a) Place the desired atomizing orifice plate in position.

(b) Fill the ice bath for the cold junction of the thermocouples with ice.

(c) Start the cooling water to the quenching unit.

(d) Set the air by-pass valve for the lowest air rate. Insert a burning gas jet into top section of the furnace

through the fuel line opening. Immediately turn on city gas to the side jets and start blower. Adjust the gas flow to the side jets to give a moderate warm-up rate for the furnace.

(e) Get barometer reading. Strain and weigh the fuel sample, then place the fuel sample in the fuel reservoir.

(f) As soon as the furnace refractory is hot enough to reignite the city gas, shut down the gas, shut down the blower, remove the jet used for ignition, place the fuel reservoir in position, make the connection between the orifice and reservoir sections of the fuel line, start the gas and start the blower. This sequence must be performed very quickly in order to prevent the metal parts at the top of the furnace from becoming too hot to handle.

(g) Read and record the sling psychrometer and the thermocouple readings.

(h) When the furnace reaches the approximate operating temperature, shut off the city gas, open the air by-pass valve wide, open the fuel throttle valve and record the time.

(i) Read and record the manometer and thermocouple readings.

(j) Start the flow into the gas sample bottle.

(k) Read and record the fuel and inlet air temperatures. Make readings of the thermocouples at approximately four-

minute intervals throughout the run. Make visual observations of the flame.

(l) Check the level of the fuel in the fuel reservoir near the end of the run. Check the manometer readings to determine whether they have remained steady.

(m) Stop the flow into the gas sample. Make the final reading of the thermocouples. Close the fuel throttle valve and record the time. Disconnect the fuel reservoir and drain out the remaining fuel. Weigh the remaining fuel.

(n) Withdraw a gas sample for analysis. Make the gas analysis.

(o) When the furnace has cooled sufficiently, shut down the blower and the cooling water.

3. Calculation and Analysis of the Results - For each run the following quantities were calculated:

(a) Average furnace temperature.

(b) The fraction of the fuel unburned.

(c) The hydrogen-carbon ratio from the gas analysis.

(d) The air-fuel ratio from the gas analysis.

(e) The percent excess air from the gas analysis.

(f) The theoretical air flow rate.

(g) The air flow rate measured by the meter.

(h) The percent excess air by meter.

(i) The air-fuel ratio measured by meter and fuel rate.

(j) The flow rate of the furnace gases.

(k) The residence time of the fuel particles in the furnace, obtained from the furnace-gas flow rate and the volume of the furnace.

(l) The volume-surface mean drop diameter.

(m) The heat release rate in terms of the heat released per hour per cubic foot of furnace volume per atmosphere.

A discussion and samples of these calculations are given in the Appendix. The agreement between the air-fuel ratio as determined from the gas analysis and that determined from the orifice meter and fuel rate was used as the basis of judging the internal consistency and the accuracy of the data for each run.

Having obtained the values listed above for each run, a correlation of the data was sought based upon the unburned fraction and a relative time factor. The correlation sought was based upon the premise that the unburned fraction should be a function of the residence time, the temperature level of the furnace and a factor representing the mixing of the fuel and air such as the relative velocity between the fuel particles and the air.

IV. RESULTS AND DISCUSSION

Performance of the Equipment

As has been previously mentioned, considerable difficulty was experienced at the beginning of the experimental work in obtaining satisfactory operation of the air blower. This difficulty was not detrimental to the results of the runs other than by placing an undue stress on the time available for completing the experimental work.

The performance of the fuel supply system was not satisfactory. During the first half of the runs the fuel rate varied from one run to the next even though the fuel orifice remained the same. Some increase in the fuel rate was expected as the air rate was increased because of greater drag forces on the fuel stream. The variation was not, however, consistent. Finally, after checking all other causes of the inconsistent variation, the fuel throttle valve was opened for inspection. The body of the valve was found to be full of sediment from heavy fuel oil, evidently remaining from the previous use of the equipment. This source of trouble had not been evident when the fuel supply system was being calibrated for fuel rate during the preliminary work of the present study. This valve was thoroughly cleaned at the same time that the fuel reservoir was moved to its final location. With the fuel reservoir

in its new location, the system still did not operate satisfactorily even after a fuel strainer was installed in the supply line just above the throttle valve. Since the success of the runs is dependent, to a great extent, upon maintaining a steady fuel rate and being able to repeat the same fuel rate for a series of five runs, the final supply system is not entirely satisfactory. With the large total head resulting from the high location of the fuel reservoir, it is necessary to throttle the fuel flow with the fuel throttle valve in order to obtain the required low fuel rates. A calibration of the throttle valve is, therefore, desirable for successful operation of the present arrangement.

The unburned fraction was obtained from the gas analysis as the ratio of the oxygen required to complete combustion to the theoretical oxygen requirement. This method was used for the sake of simplicity although the values so obtained are slightly higher than those based upon the ratio of the heating value of the unburned components to the heating value of the fuel. In either method the accuracy of determination of the unburned fraction is dependent upon the accuracy of the gas analysis. Unfortunately, the gas analysis unit used for this study was also being used for another study; thus the author never could be sure of the state of the absorbents. Several times the

absorbents were found to be saturated, but only after the analyses of one or more runs had been made invalid.

This uncertainty with regard to the gas analyses was coupled with another unfortunate circumstance which made the situation even less reparable. It was assumed, before this investigation was started, that a complete chemical analysis of the fuel would be available. Such was not the case; however, it was properly assumed that the hydrogen-carbon ratio could be accurately determined from the gas analyses. The hydrogen-carbon ratios yielded by the gas analyses varied from as low as 1.15 to as high as 1.75. Plotting the gas analyses gave an average value of 1.41 for the hydrogen-carbon ratio, which value was used in all subsequent calculations.

From the experiences related above it is concluded that, if a complete chemical analysis of the fuel had been obtained first, and if a co-worker had had complete charge of making the gas analyses and keeping the gas analysis unit in proper order, far better results could have been obtained.

Some difficulty was experienced with the gas passages in the quenching unit becoming blocked by soot when very low air-fuel ratios were used. Such low air-fuel ratios, 12 lb. air/lb. fuel or less, were not intentional, but were encountered after the relocation of the fuel reservoir. As

the quenching unit became blocked with soot, the pressure within the furnace increased, causing a decrease in the air rate. The runs in which the above action occurred could not be used for data purposes. There was some soot formed in run number 24 with an air-fuel ratio of 13 lb. air/lb. fuel and a fuel rate of 18 lb./hr. This run gave the highest heat release rate encountered during the study, namely, 183,300 B.t.u. per hour per cubic foot of furnace volume per atmosphere.

Based upon visual observations of the flame in all the runs, except those in which the sight glasses became obscured with soot, the atomization of the fuel was very good and seemed fairly uniform. There was no direct check made upon the degree of atomization attained, reliance being placed in the equation of Nukiyama and Tanisawa (9) to predict the mean drop diameter. They recommend that the equation only be used when the ratio of the air flow rate to the fuel flow rate, on a volumetric basis, is greater than 5000. Their data fitted their equation best when the air velocity through the atomizing orifice was greater than 492 ft./sec. In the runs made for this study the volumetric air rate was always considerably greater than 5000 times the volumetric fuel rate; however, the air velocity never exceeded 192 ft./sec. There is no claim made that the drop diameters obtained from the use of the equation are

truly representative of the actual mean drop diameters. The drop diameters, so obtained, are useful for the purposes of comparison. The values obtained varied only from 0.0024 inch at an air-fuel ratio of 39 lb.air/lb.fuel to 0.0029 inch at an air-fuel ratio of 13 lb.air/lb.fuel. During most of the runs, the drop diameter obtained by the equation was constant at 0.0025 inch for a considerable variation of the air-fuel ratio. The findings of other investigators (3, 8) substantiate confidence in these results.

The temperature level of the furnace measured at thermocouple No.1, which is nearest the fuel atomizer was directly dependent upon the air-fuel ratio. The temperature at thermocouple No.2, which is near the end of the furnace next to the quenching unit, was dependent not only upon the air-fuel ratio but also upon the temperature to which that section of the furnace had been raised before the run was started. The warm-up period was based upon bringing the upper section of the furnace to its approximate operating temperature. When the fuel rate was steady throughout the run the temperature at No.1 thermocouple remained quite steady; the temperature at No.2 thermocouple rose, rapidly at first, and then more slowly, to a maximum. When the fuel rate was interrupted in any way, so that the air-fuel ratio was increased, the cooling effect was immediately noticeable at thermocouple No.1. This cooling effect suggests

that the results would be improved by changing the method of mixing the fuel and air so that all the air is not introduced with the fuel through the atomizing orifice. The furnace temperature used in the calculation of the results was taken as the arithmetic mean of the temperatures measured at thermocouples No.1 and No.2.

Data from the Runs

The internal consistency of the data was based upon the agreement of the air-fuel ratio computed from the gas analysis and the measured air-fuel ratio. The error between these two quantities based on the measured ratio varied from a maximum of +11.40% for run number 9 to a minimum of zero for run number 13. These quantities should have been in much better agreement in order to be able to place any reliance in the results. The lack of agreement is attributed to the difficulties with the fuel rate and the gas analysis unit related previously.

The summary of the data and calculations is presented in Table I.

In view of the lack of internal consistency in the data, it was not expected that a correlation could be obtained. In order to test the possibilities of a correlation, the measured air-fuel ratio was plotted versus the calculated residence time for each run, each point representing one run and being labeled with the unburned fraction for

that run. This plot is shown in Figure VII. Had the data been consistent, all points representing the same unburned fraction would have fallen on smooth curves as illustrated by the dotted curves in Figure VII. The reason for the shape of the curves is as follows:

(a) For a constant air-fuel ratio, increasing the residence time should decrease the unburned fraction.

(b) For a constant residence time, there should be two air-fuel ratios at which the same unburned fraction will be obtained. The lower of these two air-fuel ratios is the one at which the unburned portion is caused by insufficient air; and the upper ratio is the one at which the unburned portion is caused by cooling of the flame from too much air.

Figure VII shows that the data obtained are not sufficiently consistent to permit a correlation. The only possible conclusion with regard to the objective of the study is that the results are negative. It does not follow, however, that a correlation of the type sought in this investigation is not possible using the same general method. With certain changes in the equipment and with more than one person operating the equipment, data of sufficient accuracy to permit their correlation could be obtained by the method of this investigation. The changes in equipment believed necessary are as follows:

(a) Install an air blower of sufficiently high pressure rating to permit the use of secondary air injection into the furnace below the atomizer and still have adequate pressure for the atomization of the fuel. The blower should have a rating of approximately 100 cu.ft./min. at a pressure of 12"-15" of water. The atomizing air would have to be metered separately.

(b) Construct a large, shallow fuel reservoir of a capacity large enough to permit the runs to last approximately one hour. This fuel reservoir should be located in a position approximately four feet above the top of the furnace. A capacity of two gallons should be adequate. An alternate possibility would be to provide a pressurized fuel reservoir, which could be maintained at constant total head on the fuel oil. The first suggestion would be much simpler.

(c) The fuel supply line should be equipped with an accurately calibrated meter to measure fuel rates as a check against the fuel rate determined from the fuel weight difference and the time of run. A Rota-meter type fluid meter would probably be suitable.

(d) The air supply system should be altered so that part of the air can be injected as secondary air below the atomizer when high air-fuel ratios are used. This change would necessitate the installation of another air meter to

measure the atomizing air. A possible arrangement incorporating this change is shown in Figure VIII.

The procedure for making the runs should be changed so that a longer warm-up period is used prior to making a test run. Based upon the experience gained in the present study, the warm-up period should be long enough to raise the temperature at the lower section of the furnace to approximately 1100°F. This action would insure a more steady temperature at the lower section during the run, and would not require a warm-up period of more than half an hour. Also, the length of the runs should be increased to about one hour in order to permit the furnace temperatures to become steady before taking the gas sample.

The recommendation that more than one person should be employed to operate the equipment is based upon the difficulty experienced by the author in trying to operate, control and maintain the equipment alone. If the proposed changes are incorporated in the arrangement, another person would be required to assist in the control of the equipment and in taking the readings.

Visual Observations

The view of the flame furnished by the upper sight glass revealed little information about the nature of the flame. The usual appearance of the flame in this sight glass was a fluttering luminosity. In runs of high air-fuel

ratios the flame disappeared from view in the upper sight glass. The ignition of the fuel was dependent upon its being heated to its flash point by radiation from the surrounding refractory surfaces. When high air-fuel ratios were used the refractory near the atomizer was cooled, thus the flame followed the hot refractory down into the furnace. In this way the volume and time available for combustion were seriously reduced, although the amount of this reduction could not be determined. In a determination of the space requirements for combustion it is most important that the flame remain fixed; therefore, provision must be made to insure that the flame is not blown away from the atomizer.

The flame, as viewed in the lower sight glass which is midway in the furnace length, ordinarily appeared as parallel streaks of luminosity, which might be described as a rain of fire.

FIGURE VII
CURVES OF FRACTION UNBURNED VS. AIR-FUEL RATIO & RESIDENCE TIME

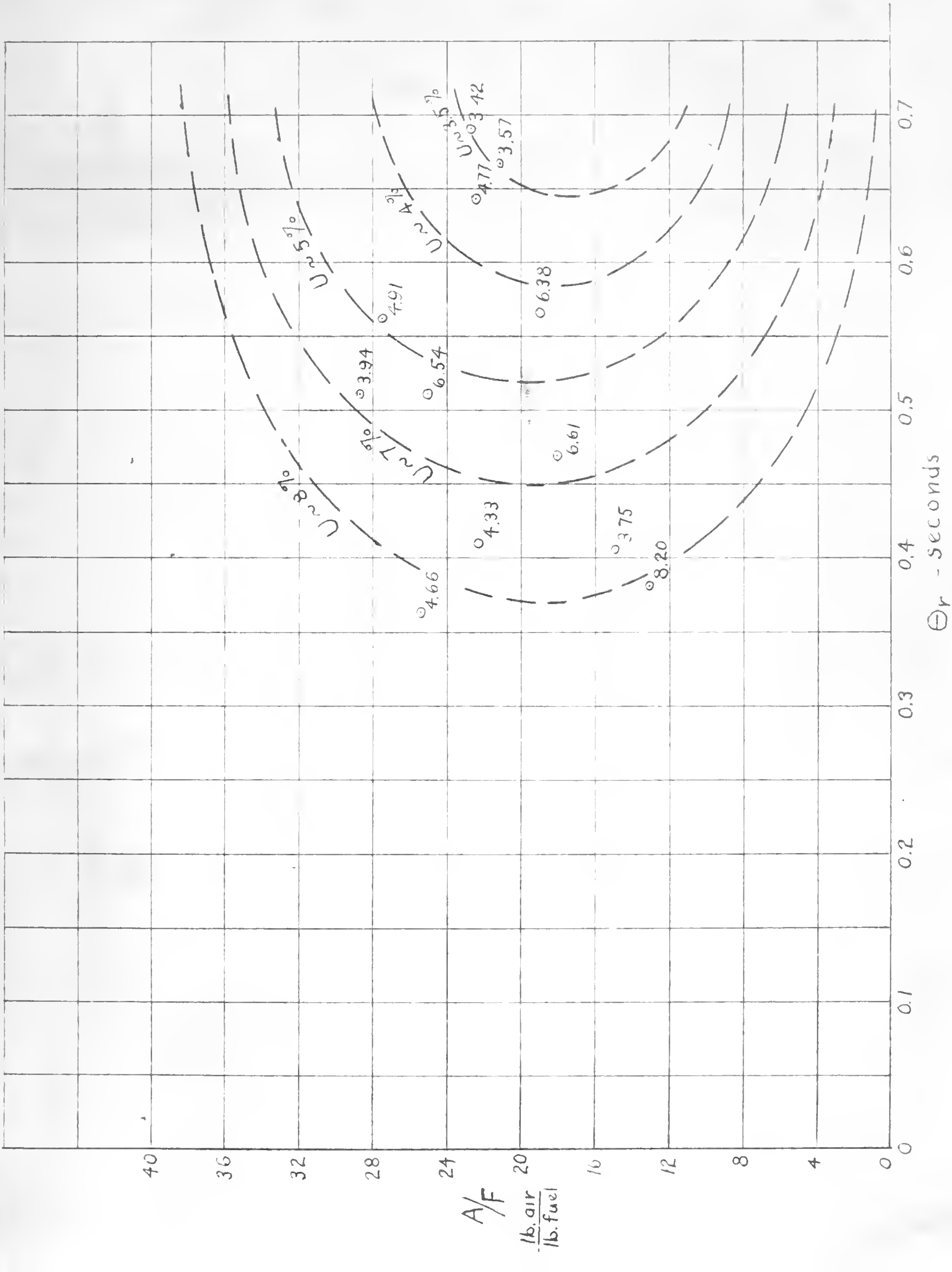
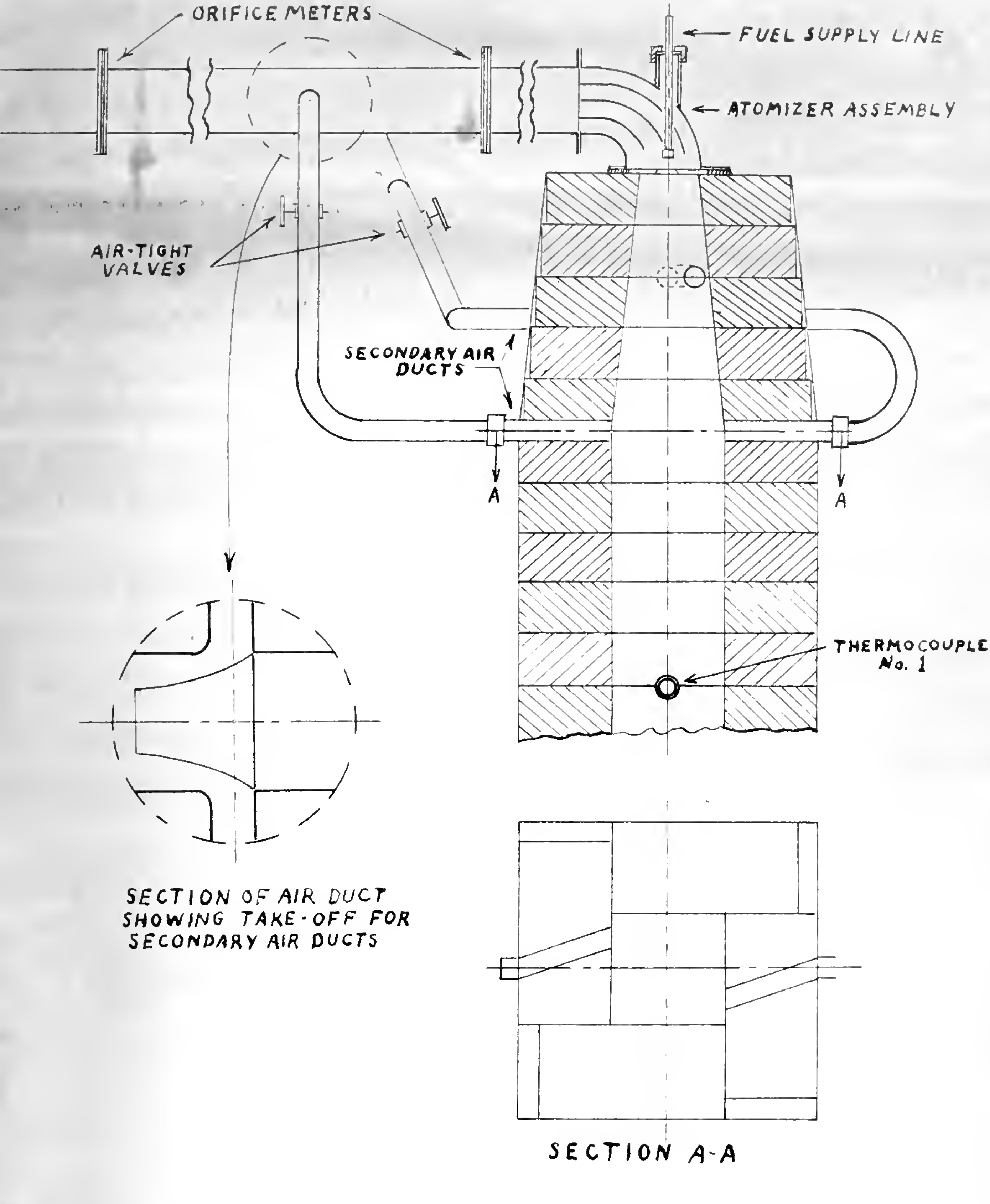


FIGURE VIII

SUGGESTED CHANGES IN ATOMIZING ARRANGEMENT



SCALE : 1½ in. = 1 ft.

TABLE I
SUMMARY OF DATA AND CALCULATIONS

Run No.	ATOMIZING Orif. in.	FUEL Orif. in.	FUEL RATE lb./min.	AIR RATE cu.ft./min.	Ave. Furn. Temp. °F	Exh. Gas Temp. °F	$(A/F)_M$ lb./lb.	$(A/F)_{GA}$ lb./lb.	E_{GA} %	E_M %	$\left(\frac{(A/F)_{GA}}{(A/F)_M}-1\right)100$ %	$\left(\frac{E_{GA}}{E_M}-1\right)100$ %	$(H_2/C)_{GA}$	U %	Θ_r sec.	D_M microns	Heat Release Rate Btu/hr.-cu.ft.-atm.
2	1.10	0.037	0.182	46.00	1634	789	19.00	18.20	31.62	36.10	- 4.20	- 12.40	0.650	6.38	0.566	64.92	111,000
3	1.20	"	0.150	58.10	1400	781	28.55	28.05	105.2	104.6	- 1.75	+ 0.57	0.610	3.94	0.510	60.21	94,500
4	1.30	"	0.189	64.50	1397	874	25.10	22.45	65.65	85.30	- 10.50	- 23.00	0.574	6.54	0.505	63.50	121,000
5	1.40	"				Fuel flow interrupted.											
6	1.00	"	0.133	37.40	1444	659	21.20	22.80	59.60	52.00	+ 7.50	+ 14.60	0.813	3.57	0.666	65.25	84,200
7	1.00	0.0465	0.123	37.45	1437	639	22.80	25.35	74.80	62.50	+ 11.10	+ 19.67	0.876	2.83	0.642	64.15	78,800
8	1.00	"	0.129	37.95	1452	653	22.50	24.15	69.60	56.80	+ 7.20	+ 22.50	0.797	4.77	0.641	63.50	81,400
9	1.10	"	0.127	46.50	1369	701	27.50	30.65	122.0	98.80	+ 11.40	+ 23.50	0.647	4.91	0.561	62.19	79,300
10	1.20	"	0.233	55.65	1779	945	18.08	16.08	18.42	29.40	- 11.00	- 37.40	0.580	6.61	0.468	63.62	143,600
11	1.30	"	0.216	65.15	1697	945	22.35	20.30	46.10	60.50	- 9.10	- 31.20	0.682	4.33	0.409	64.50	137,300
12	1.40	"	0.213	72.60	1711	961	25.40	23.20	66.40	82.45	- 8.60	- 19.50	0.689	4.66	0.363	65.43	134,500
13	1.00	"	0.126	38.30	1492	647	22.70	22.70	61.60	63.30	0	- 2.68	0.735	3.42	0.690	62.65	80,750
14	1.00	"				Gas analysis inadvertently made invalid											
RELOCATED FUEL RESERVOIR.																	
15	1.00	0.0465			Uncertain fuel rate and very heavy soot.												
16	1.00	0.028			Uncertain fuel rate and air rate.												
17	1.00	"			Interrupted fuel flow.												
18	1.00	"			Heavy soot.												
19	1.00	"			Uncertain air rate.												
20	1.20	"			Interrupted fuel flow.												
21	1.20	"			Interrupted fuel flow.												
22	1.20	"			Fuel strainer installed. Air pocket in strainer impeded fuel flow.												
23	1.20	"	0.268	54.25	1809	1234	15.00	15.43	7.29	11.28	+ 2.90	- 35.40	0.850	3.75	0.405	71.16	167,400
24	1.20	"	0.302	53.20	1933	1300	13.05	13.26	-8.20	-6.43	+ 1.50	+ 27.50	0.863	8.20	0.380	75.60	183,300

V. CONCLUSIONS

1. The equipment tested is neither adequate nor satisfactory for the purpose of obtaining data which can be utilized in a correlation of the factors affecting the space requirements for the combustion of distillate fuel. This statement is particularly true when the field of interest is in very high heat release rates.
2. By incorporating in the equipment and the procedure the changes found necessary as a result of this study, a satisfactory analysis of the factors affecting the space requirements for the combustion of distillate fuel could be made. The equipment could be used to study independently the effects of air-fuel ratio, drop size and residence time.
3. Air atomization of fuel oils with low viscosity is quite satisfactory with regard to the degree of atomization. When high air-fuel ratios are used, provision should be made to use secondary air rather than injecting all of the combustion air into the furnace with the fuel.
4. Data for the purposes of analysis and correlation should not be taken until the furnace temperature level has become steady.
5. Since the gas analyses form such an important part of

the data, the gas analysis unit must be scrupulously maintained in perfect working order.

6. The equipment cannot be properly and carefully operated by one person.
7. The equipment represents an economical method of studying the factors affecting the combustion of fuel oils.
8. The equipment, as tested, could not be used to obtain heat release rates in excess of 170,000 B.t.u./cu.ft. of furnace volume - hour - atmosphere without the formation of soot. It is interesting to note that this rate was the designed rate based upon the combustion of heavy fuel oil.

VI. RECOMMENDATIONS

1. The investigation as outlined in this report should be continued. It holds promise of yielding information useful in the design of gas turbine combustion chambers.
2. An air blower with a rating of approximately 100 cu.ft./min. at a pressure of 12" to 15" of water should be used.
3. The present fuel reservoir should be replaced by a shallow reservoir with a two-gallon capacity.
4. The air supply system should be changed so that part of the air can be injected as secondary air below the atomizer when air-fuel ratios greater than 20 lb.air/lb.fuel are used.
5. The runs should be extended to a one-hour period to permit the furnace temperature level to become steady.
6. Prior to making a run the temperature of the lower section of the furnace should be raised to approximately 1100°F.
7. More than one person should be employed to operate the equipment and take the data.
8. A gas analysis unit should be reserved for exclusive use in this study.
9. The fuel supply line should be equipped with an accurately calibrated flow meter.
10. An accurate chemical analysis of the fuel should be

obtained before starting the test runs.

11. A series of runs should be made using the reduced furnace volume which is permissible with the furnace as designed.

12. The unburned fraction should be based upon heating values rather than oxygen requirements.

13. A separate study should be made to test the validity of the equation of Nukiyama and Tanisawa when used to predict the mean drop diameter with air velocities less than 200 ft./sec.

VII. APPENDIX

A. SUPPLEMENTARY INTRODUCTION

Background of the Investigation

There were found in the literature only three examples, (4, 5 and 6), of analyses applied directly to the problem of the space requirements of fuel. One of these, by Hawthorne (4), is an unpublished paper, so that it cannot be included yet as a part of the literature. It is included here, however, as an illustration of one approach to the problem.

In 1935 Dr. I.W. Heiligenstaedt, in (5), presented a very neat design equation for the volume of combustion chambers using gas fuels. He developed his equation by ignoring the effect in variation in air supply. In certain applications the variation of the air supply would not be an important factor; however, for general application his equation cannot be considered adequate. His design equation is as follows:

$$R_v = \left(\frac{Q}{K}\right)\left(f\right)$$

R_v is the required furnace volume, meter^3.

Q is the desired heating rate, kilo-calories/hour.

K is a combustion constant dependent upon the type of mixing of the gas and air.

f is a function of the fraction unburned, the enthalpy at the end of complete combustion, the specific heat of the combustion products and the degree of preheat used.

From a study of the mixing process in several common types of gas burners, Heiligenstaedt gave the combustion constant, K, typical of each burner.

In 1940 Professor H.C. Hottel and I. McC. Stewart presented an excellent analysis of the space requirements for the combustion of pulverized coal. Their very logical method was to combine a law for the size distribution of pulverized coal and the laws of burning individual coal particles with reasonable assumptions concerning the coking characteristics of coal particles and the type of mixing. By a suitable choice of variables the results were represented graphically in terms of dimensionless quantities. These curves predict the fraction of the original fixed carbon which remains unburned at any time as a function of the chamber size, firing rate, fineness of grinding, a flame temperature, and a combustion constant. The combustion constant applies only to a given furnace and must be obtained experimentally on the furnace.

The theoretical relation developed was applied to four different coals using data obtained by other investigators. The combustion constant, when properly chosen, brought these data to within close enough agreement to conclude that the analysis could be applied to other pulverized-coal fired combustion chambers.

Professor W.R. Hawthorne, at the Massachusetts Institute

of Technology in 1946, prepared a paper, as yet unpublished, entitled, "Space Requirements for Combustion in Gas Turbines." This paper was obligingly made available to the author; it would not, therefore, be ethical to reproduce Professor Hawthorne's ideas here. It is permissible, though, to present in general terms his result, which is consistent with the theory. Professor Hawthorne's study is centered on gas turbine combustion chambers for aircraft, and was made with the object of suggesting a simple method of estimating the effect of combustion chamber dimensions on the performance of such gas turbines. In its final form, the equation which he developed gave the fraction unburned as a logarithmic function of the ratio of a burning rate parameter to a combustion intensity factor and the diameter of the combustion chamber. His equation was not supported by sufficient data to be considered conclusive; however, it is a step in the right direction.

Erkenbrack and Zoeller (3) made a macroscopic study of "Air Atomization of Fuel Oil" using diesel oil. They studied the effects of fuel orifice diameter, fuel rate, air velocity and type of injection on the characteristics of an air-atomized fuel spray. Of their conclusions, the following were of particular interest and were substantiated by the present study:

(a) With increasing fuel orifice diameter, there is no

appreciable effect on drop size at air velocities sufficient to give acceptable atomization.

(b) With increased air velocity, drop size decreases while dispersion and uniformity increase.

(c) With increased fuel rate, there is no appreciable effect on drop size at air velocities sufficient to give acceptable atomization. At low air velocities, drop size increases and uniformity decreases.

Findings of other investigators which hold particular interest for the present study are listed below.

(a) T.Y. Chang, in his investigation of "Combustion of Heavy Fuel Oil," (2), concluded that "Although combustion is usually considered as a chemical process, the physical processes of heat transfer, distillation, and diffusion are of more controlling importance in the successful utilization of heavy fuel oil."

(b) C.E. Leising and S.H. Rice studied the propagation of flame in diesel oil sprays, using pressure atomization and spark ignition. They concluded that factors which increase the degree of atomization also increase the percentage excess air at which ignition may be obtained for given conditions.

The above conclusion of Chang may also be applied to

the combustion of light fuel oils, although the chemical compositions are widely different from heavy fuel oils. The processes of combustion for heavy fuel oils and light fuel oils are also different. The combustion of heavy fuel oil takes place in three stages; preheating of the oil particles, vaporization, and heterogeneous combustion of the coke residues. From the present study, there was no evidence of the third stage, nor would it be expected.

When the increase of excess air was not sufficient to blow the flame away from the atomizer, the conclusion of Leising and Rice, stated above, was borne out by the present study.

B. PROPERTIES OF THE FUEL

The fuel oil used for this investigation was U.S. Navy Standard Diesel Oil. The properties listed below were determined by the Boston Naval Shipyard from tests on a sample of the oil used.

Gravity, A.P.I., 60°F.	36.15
Flash Point, (Pensky-Martens), °F.	182
Viscosity, 100°F., SSU	36.0
Water and Sediment	none
Conradson Carbon (10% bottoms)	0.171%
Ash	0.0073%
Corrosion Test, 3 hrs. at 212°F.	pass
Sulfur	0.119%
90% Distillation Temperature	589°F.
Color, ASTM	1-1/2
Diesel Index No.	58.2
Calorific Value (Total - Emerson Calorimeter)	19,771 B.t.u./lb.

C. MEASUREMENT OF DATA

Air

The air flow rate was measured by means of an ASME sharp-edged orifice with vena-contracta pressure taps. The upstream pressure tap is one pipe diameter, or 3.32 in., from the after face of the orifice plate. This pressure tap was used to obtain the upstream static pressure. The orifice diameter is 1.992 in., giving a diameter ratio of six-tenths. The downstream pressure tap is 1.394 in. from the face of the orifice. This tap was used to obtain the differential pressure across the orifice. The static and differential pressures were measured by means of two water manometers, with an accuracy of ± 1 mm. of water. The maximum error was 9.1%.

Fuel

The fuel sample was weighed to the nearest 0.25 oz. before and after the run, giving an overall accuracy of ± 0.0312 lb. The time of the run, or time of the fuel flow, was measured with an accuracy of ± 5 sec., or ± 0.083 min. The error in the fuel rate measured in pounds per minute is then negligible. This fuel rate, however, is only an average rate which does not represent the actual conditions unless the rate is steady throughout the run. The flow was not steady in many of the runs conducted. The unsteadiness of the fuel flow was evident from sudden, marked drops in

the furnace temperatures, which indicated interruptions in the flow.

Temperatures

The fuel and air temperatures were measured with mercury-in-glass thermometers to the nearest 0.5°F., which gives an error of 1.3% for the usual range of temperatures. These temperatures were not significant, however, in any of the computed results.

Chromel-Alumel thermocouples were used to measure the temperatures of the furnace and exhaust gases. These thermocouples have an inherent accuracy of 1.0% when used in conjunction with the Standard Table for Chromel-Alumel Thermocouples, prepared by the National Bureau of Standards. The potentiometer used to measure the potential of the thermocouples was a Leeds and Northrup, of the double-scale type. The readings were obtained to the nearest 0.1 millivolt, which gives an average error 0.3%. The total error in the temperatures measured by thermocouple was 1.3%.

Gas Analysis

With the Fisher, unitized, precision gas analysis unit, it is possible to make gas analyses with an error as small as 0.1%. Such accuracy was not attained in this investigation. The difficulties experienced with the gas analysis unit are presented in the Results and Discussion section of this report.

Original Data

The original data obtained in this investigation has been placed at the disposal of Professor H.C. Hottel.

D. COMPUTATIONS

In this section are presented only those computations which involve special formulae or definitions. All other computations used in this study involve only standard stoichiometry or conversions.

Fraction Unburned

For the purposes of this study, the fraction of the original fuel which remains unburned, U, at any time, θ, is defined as the ratio of the oxygen required to complete the combustion to the oxygen required for theoretically complete combustion. The data from the gas analysis are used for the calculation. When expressed as a percent, the equation for U is written as follows:

$$U = \frac{\text{mols } O_2 \text{ required to complete combustion}}{\text{mols theoretical } O_2} \times 100$$

Air Rate by Meter

The equation used is one recommended by The A.S.M.E. Research Committee on Fluid Meters, (1). The equation is for use only with thin-plate, sharp-edged orifice meters with vena-contracta pressure taps.

$$Q_A = 3.6408\ KY_1D_2^2 \sqrt{\frac{h_wT_1}{p_1y}}$$

Q_A = air rate in cu.ft./min. at p_1 and T_1.

The constant contains the proper conversion factors.

K = the discharge coefficient which is a function of a velocity coefficient and the ratio of the diameter of the orifice to the inside diameter of the air duct. For a given diameter ratio, K varies only with the Reynolds number at the orifice; and the variation is small for a great range of Reynolds numbers. The diameter ratio for the orifice used is 0.60, for which the values of K are given below:

Reynolds number -	35,000	50,000	75,000	100,000
K -	0.6601	0.6581	0.6564	0.6553

Y_1 = an expansion factor, which is a function of the diameter ratio, the type of fluid and the pressure ratio across the orifice. For the pressure ratios encountered in this study, this factor was always equal to unity.

D_2 = the orifice diameter in inches = 1.992 in.

h_w = the pressure differential across the orifice, measured in inches of water.

T_1 = the absolute temperature, in degrees Fahrenheit, of the fluid upstream from the orifice.

P_1 = the absolute pressure, in lb./sq.in., of the fluid, measured at the upstream pressure tap.

y = a compressibility factor, which, for the pressures involved, was always equal to unity.

In using the equation, an assumed value of K is first used to solve the equation. The Reynolds number is then obtained and the value of K checked. The variation of K is so small that, ordinarily, the first assumed value of K is near enough.

Percent Excess Air by Meter

This quantity is defined by the equation below, in which the symbol E_M represents percent excess air by meter.

$$E_M = \left(\frac{\text{air rate by meter}}{\text{theoretical air rate}} - 1\right) \times 100$$

Residence Time

The average time required by a particle of fuel to traverse the length of the combustion chamber may be expressed approximately as the quotient, Furnace Volume/Flow Rate of Furnace Gases. Expressed in this manner, the residence time, θ_r, is not exact; however, it is useful for purposes of comparison.

Mean Drop Diameter

The application of the equation of Nukiyama and Tanisawa (9) to predict the mean drop diameters in this investigation has been discussed in Results and Discussion. The equation is presented below.

$$D_M = \frac{585\sqrt{\gamma}}{V_R\sqrt{\rho}} + 597\left(\frac{\mu}{\sqrt{\rho\gamma}}\right)^{0.45}\left(\frac{1000\ Q_F}{Q_A}\right)^{1.5}$$

D_M = volume-surface mean drop diameter in microns.

V_R = velocity of air relative to the liquid at the orifice in meters/sec.

γ = surface tension of the liquid in dynes/cm.

ρ = density of the liquid in gm./cc.

μ = viscosity of the liquid in dynes-sec./cm.^{2}

Q_F = volumetric rate of the liquid in cc./sec.

Q_A = volumetric rate of the air in cc./sec.

The relative velocity, V_R, is obtained from the following equation, in which C is the discharge coefficient of the atomizing orifice:

$$V_R = \frac{Q_A}{\frac{\pi}{4}\, C\, D_A^2} - \frac{Q_F}{\frac{\pi}{4}\, D_F^2}$$

In this equation, Q_A and Q_F are in meters^3/sec.; and D_A and D_F are, respectively, the air and fuel orifice diameters in meters. The discharge coefficient of the air orifice is taken as 0.64.

For the diesel oil used, the surface tension was 28 dynes/cm. and the density was 0.844 gm./cc. The equation for D_M then reduces to the following form:

$$D_M = \frac{3370}{V_R} + 293(\mu)^{0.45}\left(\frac{1000}{(Q_A/Q_F)}\right)^{1.5} \text{ microns.}$$

<u>Heat Release Rate</u>

The heat release rate should properly be computed from a heat balance on the furnace; however, an approximation was used for the sake of simplicity of calculation and procedure. It was not desirable to have to take temperature readings of the exterior surface of the furnace and the cooling water, nor to measure the cooling water flow rate. The following approximation was used:

$$\text{Heat Release Rate} = \frac{(1-U)(LHV)(F)}{(Vol.)\ (P)} \text{ B.t.u./hr.-ft.}^3\text{-atm.}$$

U = the fraction of the fuel unburned.
LHV = the lower heating value of the fuel in B.t.u./lb.
= 18,775 B.t.u./lb.
F = the fuel rate in lb./hr.
Vol.= the furnace volume in ft.^{3}= 1.698 ft.^{3}
P = the absolute pressure within the furnace in atmospheres.

This approximation is not too far wrong, for comparative purposes, when the unburned components are of the same composition from one run to the next.

E. SAMPLE CALCULATIONS

Data

Run No.13

Atomizing Orifice = 1.00 in. Fuel Orifice = 0.0465 in.

Barometer = 756.2 mm. Hg.

Wet Bulb = 54°F. Dry Bulb = 76°F.

Room Temp. = 76°F.

Sp. Humidity = 0.00395 $\frac{\text{lb. } H_2O}{\text{lb. air}}$

Fuel Wt.before run=10 lb.14.5 oz. Time run started=1141:00
Fuel Wt. after run= 7 lb. Time run ended =1212:00
Fuel Consumed = 3.906 lb. Total time = 31.00 min.

Fuel Temp. = 75.5°F. Fuel Rate = 0.126 lb./min.

Inlet Air Temp. = 80.0°F.

Chamber Press. = 0.6 cm. H_2O

Orifice Meter Pressures

p_1 = 23.50 cm. H_2O h_w = 1.15 cm. H_2O

Thermocouple Readings (millivolts)

Time	1140	1144	1148	1153	1158	1201	1207	1210	t_{ave}
TC_1	39.45	41.70	41.80	41.50	40.20	39.15	37.00	35.40	1750°F.
TC_2	20.60	23.35	25.80	27.90	29.10	29.40	29.45	29.40	1234°F.
TC_3	11.90	13.55	13.68	14.38	14.30	14.13	13.87	13.74	647°F.

Furnace Temp. = 1492°F.(Average)

Gas Analysis

CO_2 .... 8.835%
O_2 .... 8.675%
Combustibles 0.914%
  Atoms C in combustible = 0.914
  O_2 required to burn = 0.457
N_2 .... 81.576%
100.000%

Calculations

Basis: 100 mols dry exhaust gases = 100 mols G

O_2 utilized $= (\text{mols } N_2) \times \frac{(\text{mols } O_2)}{(\text{mols } N_2)} - (\text{mols } O_2)$

$= (81.576)\frac{(0.201)}{(0.791)} - (8.675) = 12.875 \text{ mols } O_2$

O_2 necessary = O_2 utilized + O_2 required to complete combustion

$= 12.875 + 0.457 = 13.332 \text{ mols } O_2$

Fraction unburned $= U\ (\%) = \dfrac{O_2 \text{ required to complete combustion}}{O_2 \text{ necessary}/100}$

$= 45.7/13.332 = 3.42\%$

Total Carbon = 9.749 atoms C/100 mols G

Total Hydrogen = 7.16 mols H_2/100 mols G

H_2/C = 7.16/9.749 = 0.735

Air-Fuel ratio by gas analysis, lbs.air/lb.fuel;

$$A = (\text{mols } N_2)\left(\frac{1 \text{ mol air}}{0.791 \text{ mol } N_2}\right)\left(\frac{28.97 \text{ lb.air}}{1 \text{ mol air}}\right)$$

$$= (81.576)\left(\frac{1}{0.791}\right)(28.97) = 2990 \text{ lb. air}$$

$$F = (12.01)(\text{total carbon}) + (2.02)(\text{total hydrogen})$$

$$= (12.01)(9.749) + (2.02)(7.16) = 131.5 \text{ lb. fuel}$$

$(A/F)_{GA} = 2990/131.5 = 22.70$

$$\text{Excess Air} = \frac{(\text{mols } O_2 \text{ supplied}) - (\text{mols } O_2 \text{ necessary})}{(\text{mols } O_2 \text{ necessary})/100}$$

$$E_{GA} = \frac{(21.55) - (13.332)}{13.332} \times 100 = 61.6\%$$

$$\text{Theoretical Air rate} = \frac{\text{mol air}}{\text{lb. fuel}} \times \frac{\text{lb. fuel}}{\text{min.}} \times \frac{\text{cu.ft.air}}{\text{mol air}}$$

$$= (0.481)(0.126)(359)\left(\frac{540}{492} \times \frac{760}{773}\right)$$

$$= 23.45 \text{ cu.ft.air/min.}$$

Air Rate by Meter:

$$Q_A = 3.6408KY_1D_2^2 \sqrt{\frac{h_w T_1}{P_1 y}} \text{ cu.ft./min.}$$

Assume Reynolds number at the orifice = 30,000, for which

$K = 0.661$ $\qquad T_1 = 80 + 460 = 530^\circ$F.abs.

$Y_1 = 1$ $\qquad y = 1$

$D_2 = 1.992$ in. $\qquad D_2^2 = 3.96$ sq.in.

$h_w = 1.15$ cm.H_2O = 0.453 in. H_2O $\qquad p_1 = 773$ mm.Hg. = 14.92 psia

$$Q_A = (3.4608)(0.661)(1)(3.96) \left(\frac{(0.453)(540)}{(14.92)(1)}\right) = 38.30 \text{ cu.ft./min.}$$

Check on the assumed Reynolds number:

$$(Re) = \frac{\rho VD}{\mu}$$

V = velocity through orifice, ft./sec.

D = orifice diameter, ft.

ρ = air density, lb./cu.ft.

μ = air viscosity, lb./sec.ft.

V = (38.3 cu.ft./min)(1 min./60 sec.)(1/0.0216 sq.ft.)=29.55/ft.sec.

$\rho = 0.0748$ lb./cu.ft. $\qquad D = 0.166$ ft.

$\mu = 12.1 \times 10^{-6}$ lb./sec.ft.

$(Re) = (0.0748)(29.55)(0.166)/(12.1 \times 10^{-6}) = 30,350$

The above Reynolds number is near enough the assumed value that the value of K need not be changed.

Percent Excess Air by Meter:

$$E_M = \frac{\text{Air rate by meter - Theoretical air rate}}{\text{Theoretical air rate}} \times 100$$

$$= \frac{38.30 - 23.45}{23.45} \times 100 = 63.3\%$$

Percent Error in Excess Air:

$$\left(\frac{E_{GA}}{E_M} - 1\right) \times 100 = \left(\frac{61.6}{63.3} - 1\right) \times 100 = (-)\ 2.68\%$$

Measured Air-Fuel Ratio:

$$(A/F)_M = \frac{38.30 \text{ cu.ft.air}}{0.126 \text{ lb. fuel}} \times \frac{1 \text{ mol air}}{359 \text{ cu.ft.}} \times \frac{28.97 \text{ lb.air}}{1 \text{ mol air}} \times \frac{492}{540} \times \frac{773}{760}$$

$$= 22.70 \text{ lb.air/lb.fuel}$$

Percent Error in Air-Fuel Ratio:

$$\frac{(A/F)_{GA}}{(A/F)_M} - 1 \quad \times 100 = \left(\frac{22.70}{22.70} - 1\right) \times 100 = 0.00\%$$

Furnace Gases:

By carbon balance: $\frac{7.44 \text{ atom C}}{100 \text{ lb. fuel}} \times \frac{100 \text{ mol G}}{9.749 \text{ atom C}} = 0.7625 \frac{\text{mol G}}{\text{lb.fuel}}$

Combustion Air $= \frac{81.576 \text{ mol } N_2}{100 \text{ mol G}} \times \frac{100 \text{ mol air}}{79.1 \text{ mol } N_2} = \frac{103.1 \text{ mol air}}{100 \text{ mol G}}$

H_2O in Comb.Air $= \frac{0.00635 \text{ mol } H_2O}{\text{mol air}} \times \frac{103.1 \text{ mol air}}{100 \text{ mol G}} = \frac{0.655 \text{ mol } H_2O}{100 \text{ mol G}}$

H_2O from H in fuel $= \frac{7.16 \text{ mol } H_2O}{100 \text{ mol G}}$

Total $H_2O = \frac{(7.16 + 0.655) \text{mol } H_2O}{100 \text{ mol G}} \times \frac{0.7625 \text{ mol G}}{\text{lb. fuel}} = \frac{0.0596 \text{ mol } H_2O}{\text{lb. fuel}}$

Total gases $= 0.7625 + 0.0596 = \frac{0.822 \text{ mol gases}}{\text{lb. fuel}}$

Residence Time:

Furnace Volume = 1.698 cu.ft. Furnace temp. = 1492 + 460
= 1952°F. abs.

Fuel Rate $= \frac{0.126 \text{ lb. fuel}}{\text{min.}} \times \frac{1 \text{ min.}}{60 \text{ sec.}} = 2.10 \times 10^{-3}$ lb.fuel/sec.

$$\frac{\text{cu.ft.gases}}{\text{sec.}} = \frac{2.10\times10^{-3} \text{lb.fuel}}{\text{sec.}} \times \frac{0.822 \text{ mol gases}}{\text{lb.fuel}} \times \frac{359 \text{ cu.ft.}}{1 \text{ mol}} \times$$

$$\frac{1952}{492} \times \frac{760}{760} = \frac{2.46 \text{ cu.ft. gases}}{\text{sec.}}$$

θ_r = Vol./cu.ft. gases/sec.

$$\theta_r = \frac{1.698}{2.46} = 0.69 \text{ sec.}$$

Mean Drop Diameter:

$$Q_A = \frac{38.3 \text{ cu.ft.}}{\text{min.}} \times \frac{1 \text{ min.}}{60 \text{ sec.}} \times \frac{0.0283 \text{ cu.m.}}{1 \text{ cu.ft.}} = \frac{0.01808 \text{ cu.m.}}{\text{sec.}}$$

Q_A = 0.6385 cu.ft./sec. $\quad D_A$ = 1.00 in. $\quad D_A^2$ = (1/144)sq.ft.

$$V_A = \frac{0.6385 \times 4 \times 144}{\pi \times 0.64 \times 1} = 182.8 \text{ ft./sec.} = 55.70 \text{ m./sec.}$$

$$Q_F = \frac{2.10 \times 10^{-3} \text{ lb. fuel}}{\text{sec.}} \times \frac{1 \text{ cu.ft. fuel}}{52.6 \text{ lb.fuel}} \times \frac{0.0283 \text{ cu.m.}}{1 \text{ cu.ft.}}$$

$$= 1.129 \times 10^{-6} \text{ cu.m./sec.}$$

$D_F^2 = 1.395 \times 10^{-6}$ sq.m. $\qquad Q_A/Q_F = \dfrac{1.808 \times 10^{-2}}{1.129 \times 10^{-6}} = 16{,}000$

$$V_F = \frac{4 \times 1.129 \times 10^{-6}}{\pi \times 1.395 \times 10^{-6}} = 1.03 \text{ m./sec.}$$

$$V_R = V_A - V_F = 55.70 - 1.03 = 54.67 \text{ m./sec.}$$

μ = 0.0422 dyne-sec./cm.

$$D_M = \frac{3370}{V_R} + 293\,(\mu)^{0.45}\left(\frac{1000}{Q_A/Q_F}\right)^{1.5} \quad \text{microns}$$

$$D_M = \frac{3370}{54.67} + 293(0.0422)^{0.45}\left(\frac{1}{16}\right)^{1.5}$$

$$= 61.55 + 1.10 = 62.65 \text{ microns} = 0.00246 \text{ in.}$$

Heat Release Rate:

$$\text{Heat Release Rate} = \frac{(1-U)(LHV)(F)}{(\text{Vol.})\ (P)} \qquad \frac{\text{B.t.u.}}{\text{hr.-cu.ft.-atm.}}$$

U = 3.42% or 0.0342

LHV = 18,775 B.t.u./lb. fuel

F = 0.126 lb.fuel/min. x 60 min./hr. = 7.56 lb.fuel/hr.

Vol. = 1.698 cu.ft.

P = 1 atmosphere

$$\text{Heat Release Rate} = \frac{(0.9658)(18{,}775)(7.56)}{(1.698)\ (1)}$$

$$= 80{,}750 \text{ B.t.u./hr.-cu.ft.-atm.}$$

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